Slag Tap Firing System for a Low Emission Boiler

by

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ABSTRACT

The objective of the U.S. Department of Energy's Low Emission Boiler System (LEBS) program is to dramatically improve the environmental performance of future electric power generating plants fired with pulverized coal. The Low Emission Boiler System developed by the DB Riley team under this project incorporates a low-NOx slag-tap boiler. This firing system converts the fly ash into a vitrified form which is useful as a byproduct, and which is more easily handled and disposed of if necessary. In addition, the down-fired, or U-fired, slag tap system is adaptable to a broad range of fuels, including those with low volatile or high ash content. The very high NO_x emissions typical of slag tap firing are controlled with a combination of advanced low-NO_x burners, air staging, and fuel staging (reburning). Tests at DB Riley's 30 MW_t U-fired facility have demonstrated NOx levels of less than 0.2 lbs/MBtu leaving the firing system, minimizing the need for post combustion cleanup. Commercial demonstration is planned at an 80 MW Proof-of-Concept (POF) Facility.

This paper presents an overview of the LEBS Project, test results from the firing system development work, and a design for a Proof-of-Concept demonstration.

INTRODUCTION

DB Riley, Inc., is leading an industry team in a DOE-supported program to develop a new generation of coal-fired Low-Emission Boiler Systems (LEBS)[(1)]. The project team consists of DB Riley, Inc., Sargent & Lundy LLC, Thermo Power Corporation, the University of Utah, and Reaction Engineering International.

The project goal is to develop a system which will meet emission limits of 0.1 lbs/million Btu NOx, 0.1 lbs./million Btu SO2, and 0.01 lbs./million Btu for particulate. Additional objectives include improved ash disposability, reduced waste generation, reduced toxic substance emission, and efficiency exceeding 42% net plant efficiency (HHV basis).

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The team has developed a LEBS capable of meeting all emission and performance goals. The system includes a supercritical boiler fired with a low-NO_x, slag-tap firing system, a regenerable desulfurization system with de-NO_x capability, advanced low-temperature heat recovery, and particulate removal.

After a review of the LEBS concept, this paper will describe in more detail the 30 MW_t (nominally 10-MW_e equivalent) firing system tests, and the design for a Proof-of-Concept (POC) Facility. The tests have demonstrated that application of an advanced low-NO_x burner, in combination with either air staging alone, or with coal reburning (staged fuel), can reduce NO_x to less than 0.2 lbs/million Btu (86 g/GJ) in a U-fired slag tap system. Low NOx operation has been demonstrated with 1) a high-sulfur, Midwestern coal; 2) a medium sulfur, Eastern coal; and 3) with a subbituminous Western coal.

THE LEBS DESIGN CONCEPT

Figure 1 shows the LEBS design concept for a 400 MW_e commercial generating unit (CGU) developed by the DB Riley team. The design includes a supercritical boiler fired with a low-NO_x, slag tap U-firing system, the copper oxide regenerable flue gas desulfurization system with de-NO_x capability[(2)], advanced low temperature heat recovery, and high efficiency particle removal. The LEBS CGU design is based on a supercritical steam cycle operating at 4500 psi (310 bar) and 1100°F (593 C) with double reheat to 1100°F (593 C). The net plant efficiency for a LEBS CGU firing high sulfur coal has been calculated at 42.2% based on higher heating value.

The CGU design, in addition to meeting the performance and emission goals, eliminates flyash and scrubber solids waste streams. It has significant benefits to the environment because:

- The ash in the coal is converted into non-leachable, inert slag by the firing system instead of flyash;
- The sulfur in the coal is converted into either elemental sulfur, sulfuric acid, or ammonia sulfate by the flue gas desulfurization system;
- Nitrogen oxides are controlled primarily by the firing system, requiring only moderate post combustion treatment;
- Less carbon dioxide is emitted per megawatt of electricity due to a high steam cycle efficiency.

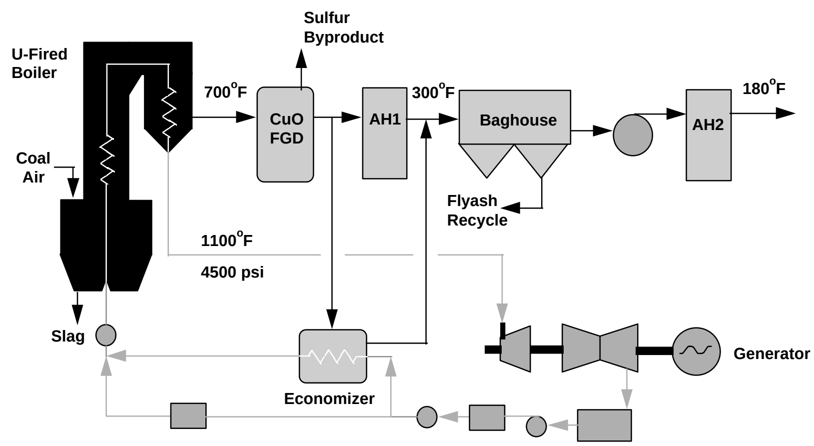

Figure 1. The Low Emission Boiler Commercial Generating Unit Concept.

THE U-FIRING SYSTEM

The CGU firing system is based on the well established U-fired slagging boiler design[(3)]. As shown in Figure 2, the fuel is fired down into a refractory chamber. Slag forms on the chamber walls and bottom, and on the slag screen at the chamber exit. The slag is continuously tapped from the combustion chamber, quenched, and dewatered. The hot gases then flow up and out through the slag screen, and final air is added to complete combustion.

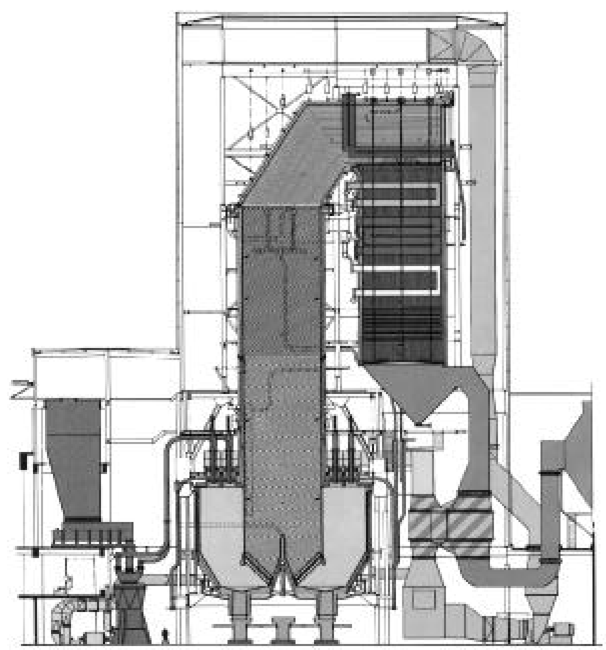

Figure 2. Commercial 320 MW_e U-fired Benson Boiler Using Two Chamber Design.

Over fifty U-fired slagging boilers have been constructed. The U-firing system can fire a wide range of coals under varying utility operating conditions. When not recycling the flyash, the firing system converts over one half of the coal ash into slag. As it is quenched, the slag converts into a low volume, inert, vitreous granulate. Almost all of the coal ash can be converted to slag by recycling the flyash back to the boiler, as is the standard practice in many operating units.

High temperatures are needed to maintain slag flow in U-fired boilers, resulting in high NO_x emissions. In early U-fired slagging boilers, high swirl burners produced NO_x emissions as high as 1.6 lbs/10^6Btu (688 g/GJ). Applying air staging and burner improvements reduced the emission level to 0.8 lbs/10^6Btu (340 g/GJ) for currently operating units. A major challenge for the DB Riley team was to satisfy the LEBS emission goals while operating at high temperature slagging conditions to satisfy the reduced waste generation goal. A NO_x emission target of 0.2 lbs/10^6Btu (86 g/GJ) was established for the firing system to minimize the amount of NO_x reduction for the post combustion emissions control system.

The approach for achieving the combustion system NO_x emission target was to apply the controlled combustion venturi (CCV®) dual air zone coal burner in combination with advanced air staging and coal reburning techniques in the U-fired slagging system. DB Riley originally developed the CCV® dual air zone burner, shown in Figure 3, for low-NO_x dry-fired applications[(4)].

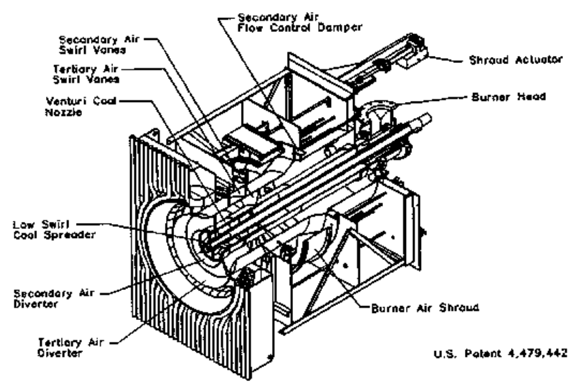

Figure 3. DB Riley Controlled Combustion Venturi (CCV®) – Dual Air Zone Burner.

DB Riley built a 100 million Btu/hr U-fired combustion test facility to test the low NO_x firing concept in a U-fired slagging system for the U.S. DOE LEBS program. An existing CCV® dual air zone test burner was modified for down-firing and installed in the U-fired test facility.

THE U-FIRED TEST FACILITY

Figure 4 shows the U-fired test facility (UFTF) constructed to test the LEBS firing system at 100 million Btu/hr thermal (29 MW_t) input. It matches residence time, or volumetric heat release, of a commercially operating U-fired slagging boiler. It includes a refractory-lined chamber fired by one burner mounted on the roof, a slag tap system, slag screen, and an upflow section corresponding to the lower part of the radiant furnace in the commercial boiler. It is integrated with an existing 100 million Btu/hr wall fired facility, sharing common coal pulverizer, air supply and preheat, and final flue gas cleanup systems.

Figure 5 shows the air staging and coal reburning locations in the test facility. These locations provided zones of controlled stoichiometry in the furnace. Reburn residence times were varied by changing the reburn injection and final air locations.

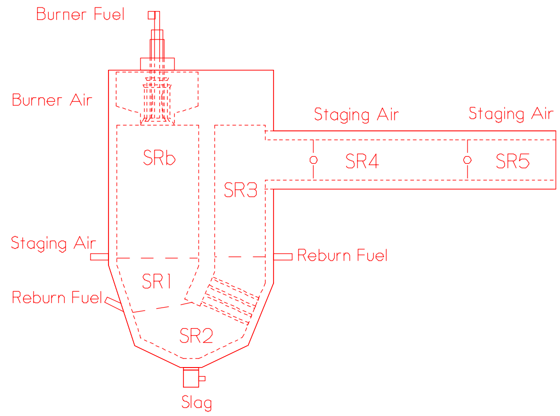

Figure 4. The 100 million Btu/hr (30 MW_t) U-fired Test Facility.

Figure 5. U-fired Test Facility Air Staging and Coal Reburning.

TEST PROGRAM OVERVIEW

Most of the tests conducted to date in the U-fired test facility were completed with the Illinois No. 5 coal from the Turris Mine site. Illinois No. 5 is a high sulfur, high volatile Bituminous C coal. Selected conditions were also tested with a medium sulfur, high volatile Bituminous A coal blend from the Toms Creek Preparation Plant in Coeburn, Virginia. This coal was significantly lower in both sulfur and volatile matter than the Turris coal. In addition, the ash fusion temperature of the Toms Creek coal is much higher, with a calculated T_{250} of 1566 C (2850 F), compared to 1343 C (2450 F) for the Turris coal ash. The operability of the UFTF with continuous slag tapping with this higher ash fusion temperature was an important result. The NOx results for the two coals were very similar, and are not distinguished by coal type in the following discussion of NOx results.

Additional tests were recently completed with a Montana subbituminous coal from the Powder River Basin (PRB coal). This is a low sulfur, high-moisture, high volatile coal. The performance of this coal was much different than the others, and preliminary results are discussed separately.

Several burner coal nozzle variations were tested to provide the lowest NO_x emissions while maintaining slag production and carbon burnout. The test burner was also modified to simulate burners installed in a commercially operating U-fired slagging boiler. This burner modification is identified in this paper as the baseline burner, because it was intended to provide a comparison between the test facility and an existing U-fired boiler.

NO_x EMISSION RESULTS

Figure 6 shows the NO_x results for the baseline burner compared to the CCV® dual air zone burner, for air staging. NO_x emissions are plotted against burner stoichiometry. The total excess air was maintained at 15%. The CCV® dual air zone burner NOx performance was significantly better than the baseline burner, and its NO_x emissions were remarkably low for slag tap operation. The CCV® dual air zone burner produced a narrow, well-attached flame. The baseline burner produced a wide, detached flame with rapid mixing of the burner air and coal. This difference in flame shape could be seen in the flame videos, as shown in Figure 7, and the slag deposition patterns in the furnace.

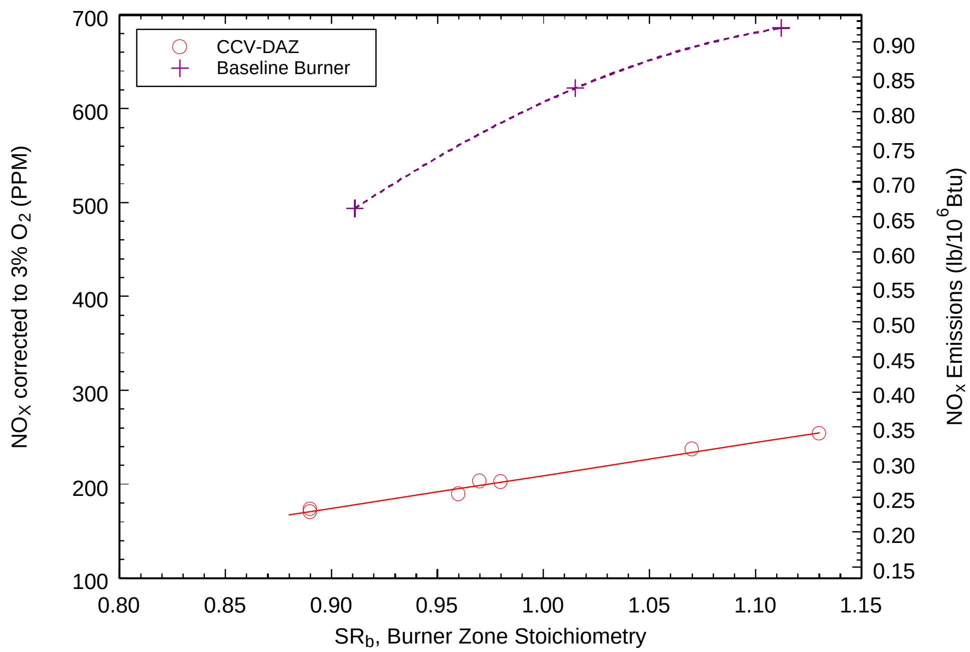

Figure 6. NO_x versus Burner Stoichiometry, Baseline Burner and CCV® Dual Air Zone Low NO_x Burner.

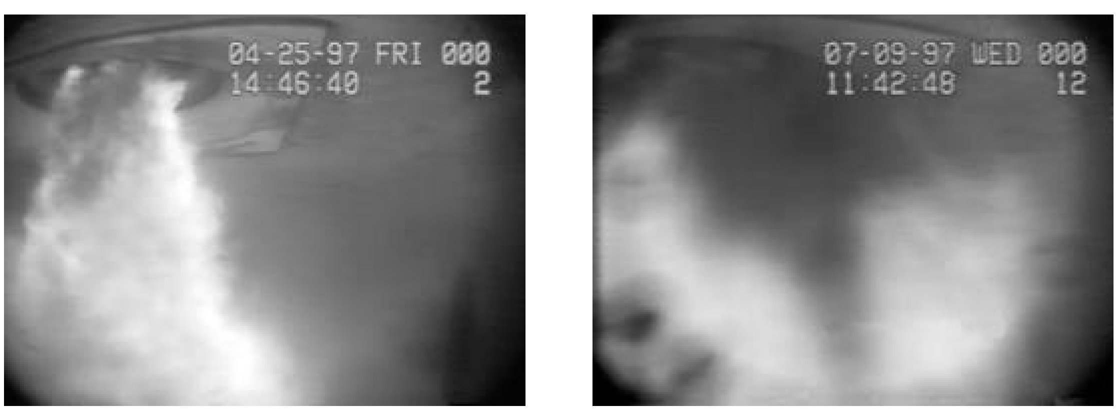

Figure 7. CCV® Dual Air Zone (left) and Baseline Burner (right) Flames.

Figure 8 shows that the NO_x levels in the U-fired test facility were reduced to below 0.2 lbs/10^6Btu (86 g/GJ) by introducing air staging farther downstream, increasing the residence time in the reducing zone. This NOx reduction was also achieved with coal reburning at about 10% of the total firing rate to lower the stoichiometry in the upflow section to 0.9.

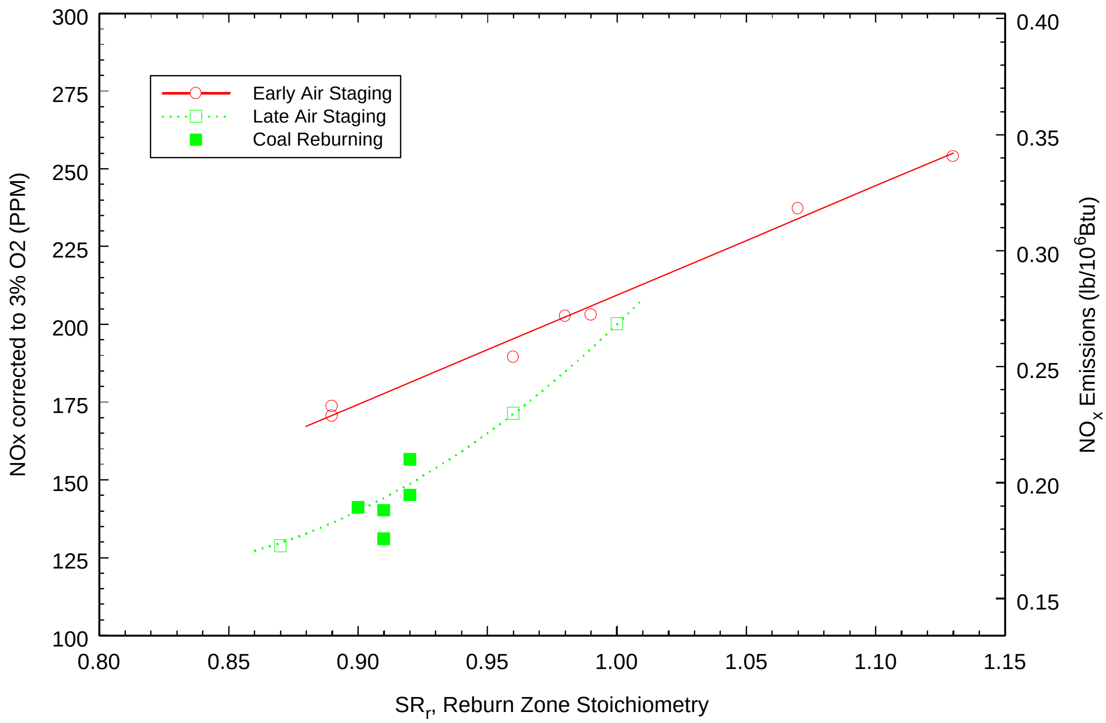

Figure 8. NO_x versus Reburn Zone Stoichiometry, Effect of Air Staging and Coal Reburning.

Although coal reburning and air staging operate at similar stoichiometries, coal reburning avoids a fuel rich zone in the firing chamber. Coal reburning also separates the substoichiometric zone from the slagging chamber of the furnace. Under U-fired reburn conditions, the firing chamber slag tap was operated at stoichiometries of unity or higher.

The effect of reburning zone residence time on NO_x emissions is illustrated in Figure 9. Coal reburning required sufficient residence time to be effective. In the test facility, the maximum residence time for injecting reburn fuel after the slag screen was 1 second. A longer residence time was tested by injecting the reburn fuel before the slag screen.

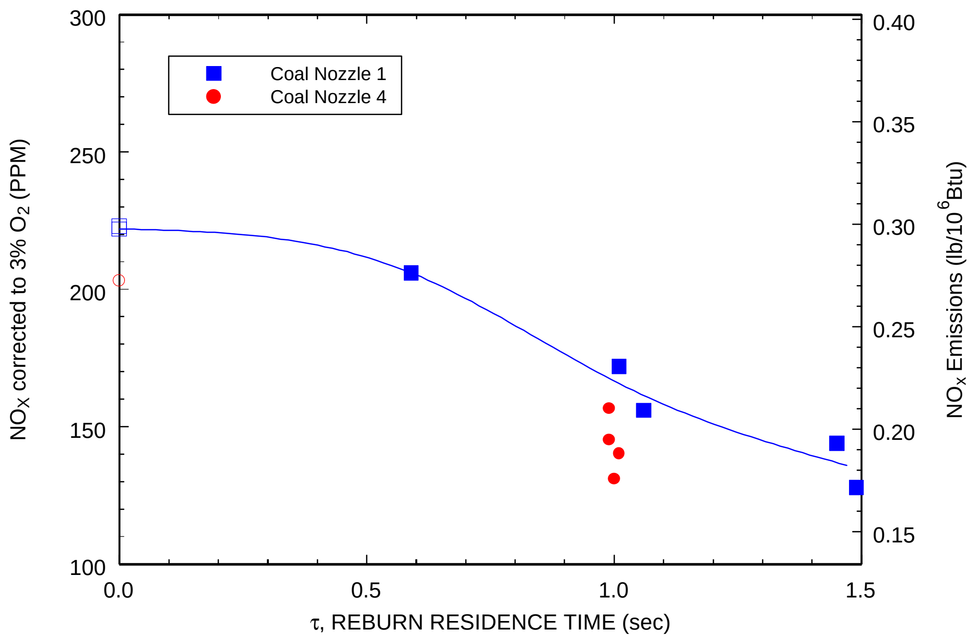

Figure 9. NO_x versus Reburn Residence Time.

Western Coal

Limited testing was recently completed with PRB coal. This coal produced significantly lower NO_x emissions than the Illinois No. 5 coal. In addition, the minimum NO_x level for PRB coal was observed in the range of 0.95 to 1.0 burner stoichiometry, whereas NO_x continued to decrease with burner stoichiometry down to approximately 0.85 SR_b with the Illinois No. 5 coal. When staging air was configured for longer SR_b residence time, NO_x emissions with PRB coal were reduced to approximately 0.12 lbs/10^6Btu (52 g/GJ), at a burner stoichiometry of 0.95-1.0.

The firing rate in the UFTF was limited by pulverizer capacity to about 80 million Btu/hr (23 MW_t) in the UFTF, due to the high moisture and low heating value. Most of the tests with the Illinois No. 5 coal were completed at 100 million Btu/hr (29 MW_t) input. However, comparison of results for both coals at 80 million Btu/hr indicated that the effect of firing rate on NO_x was minor, relative to the effect of coal properties.

Carbon in the fly ash was very low, due both to the higher reactivity of PRB coal, and the relatively high burner stoichiometry under which NO_x was minimized. The major problem with UFTF operation firing PRB coal was with slag tap operation. The laboratory ash fusion temperatures for the PRB and Illinois coals were similar. However, while there were no operational problems during the Illinois No. 5 tests (including daily start up and shutdown, and operation down to 80 million Btu/hr), slag discharge could not be maintained with PRB firing, and the slag layer on the wall of the firing chamber deteriorated over time. The PRB coal ash content was below the minimum value recommended for slag tap furnaces. Other ash properties may influence slagging in ways not indicated by laboratory fusion temperatures. This issue is being investigated in greater detail.

SLAG AND FLYASH CHARACTERISTICS

Slag and particulate flyash samples were analyzed to characterize carbon burnout for the U-fired test facility. The carbon in the slag averaged less than 0.5% over a large range of firing conditions, never exceeding 2%. Flyash carbon content was higher, and varied with test conditions. However, since over half of the coal ash was converted into slag, the overall heat loss due to unburned carbon was low, averaging less than 1% over all conditions tested. Coal reburning generally gave lower values of carbon loss than air staging for equivalent NO_x levels. Nearly all the carbon loss was associated with carbon in the flyash. In a commercial system, the carbon loss would be reduced even further by recycling the flyash into the firing chamber.

Toxicity Characteristic Leaching Procedure (TCLP) results for the slag are shown in Table 1. The leachable metals in the slag were well below 1990 RCRA toxicity limits. Slag produced in the LEBS U-fired system is suitable for disposal as well as byproduct uses.

Table 1
Average TCLP Analysis*

	Firing Coal	Detection Limit	1990 RCRA Toxicity Limit
Total Arsenic as As (mg/L)	BDL	0.20	5
Total Barium as Ba (mg/L)	1.07	0.05	100
Total Cadmium as Cd (mg/L)	BDL	0.05	1
Total Chromium as Cr (mg/L)	BDL	0.05	5
Total Lead as Pb (mg/L)	0.29	0.10	5
Total Mercury as Hg (mg/L)	BDL	0.001	0.2
Total Selenium as Se (mg/L)	BDL	0.20	1
Total Silver as Ag (mg/L)	BDL	0.05	5

* UFTF slag samples: Average of three firing Illinois No. 5 coal.

SCALE-UP OF TEST FACILITY RESULTS

Very low levels of NO_x were achieved in the U-fired test facility compared to current operating slagging boilers. Since the test facility was designed to simulate the volumetric heat release rate (equivalent to residence time), of a full scale boiler, the surface area heat release rate in the test facility is lower than in a full scale unit. To understand the influence of furnace scale and surface area heat release, we compared the baseline burner test facility results to field data from a commercially operating U-fired slagging furnace[3]. Figure 10 compares the NO_x emissions of the test facility and the field boiler as a function of surface area heat release. This figure shows that the U-fired test facility firing a single baseline burner simulated the NO_x emissions of the field boiler with multiple burners operating at 50% load. These data suggest that the NO_x emissions observed in the test facility would increase about 20% for a factor of two increase in the surface area heat release.

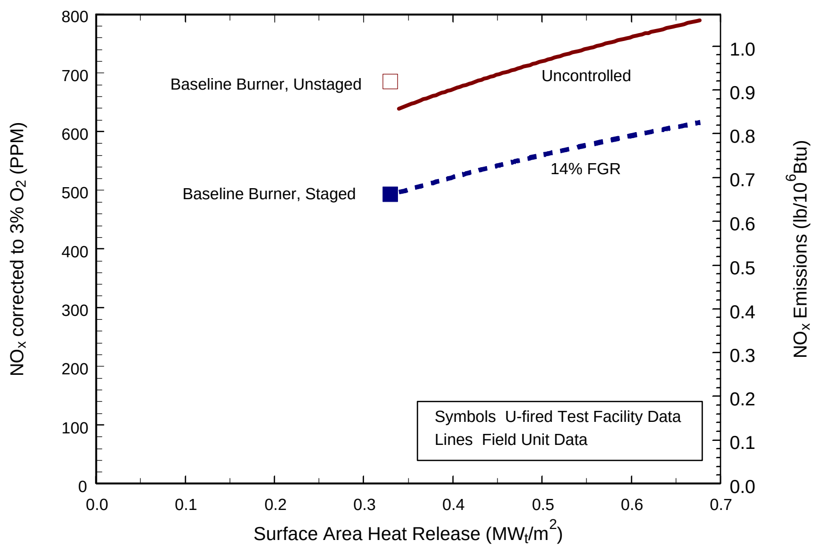

Figure 10. NO_x versus Heat Release, Scale-up of U-fired Test Facility Results.

THE PROOF OF CONCEPT FACILITY

Information gained from the U-fired test facility is being used in the design of the LEBS proof of concept facility to demonstrate the low-NO_x firing system at a commercial scale. Figure 11 shows the POC U-fired boiler designed for 80 MW of electric power with a conventional steam cycle. Four, 200 million Btu/hr CCV® dual air zone burners will be used to fire the coal. Coal reburning will take place in the upflow section of the furnace after the slag screen.

The POC facility will demonstrate a full-scale, U-fired low NO_x slag tap fired boiler designed for continuous operation and capable of meeting the service life and availability demands for commercial operation. It will provide a commercial scale reference plant for this technology.

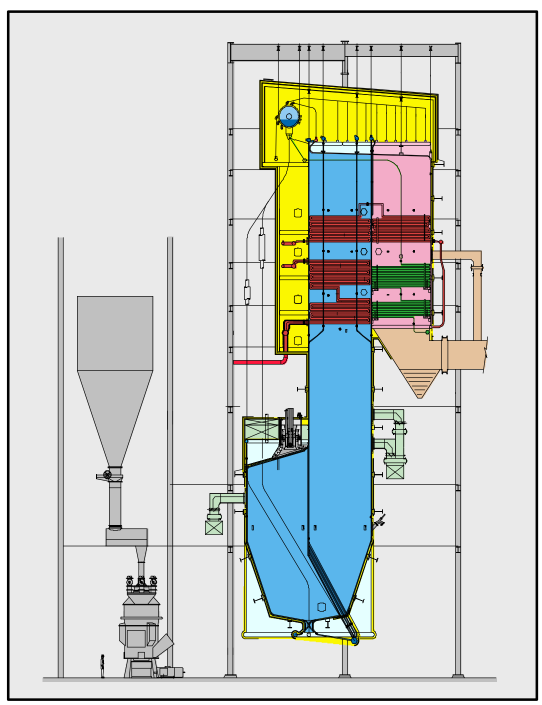

Figure 11. POC U-Fired Boiler.

CONCLUSIONS

The LEBS NO_x emission combustion system goal of 0.2 lbs/10^6Btu (86 g/GJ) was demonstrated in a U-fired test furnace using the CCV® dual air zone burner with either advanced air staging or coal reburning. When firing the burner alone, without air or fuel staging, the NO_x levels were still very low for slag tap conditions. These results were achieved while converting the coal ash into an inert, low volume, non-leachable solid. Coal reburning provided independent control of the slag tap stoichiometry and reducing zone stoichiometry. Independent control was beneficial in maintaining conditions for good slag production as found in commercially operating slag tap firing systems.

Since over half of the coal ash was converted to low carbon slag, the overall carbon loss was small (1% on a heat loss basis), even under very low NO_x firing conditions. In a commercial system, the carbon loss would be reduced even further by reinjecting the flyash back into the firing chamber.

The test facility provided a valid simulation of the effectiveness of NO_x control measures applied to a high temperature U-fired slagging boiler. The U-fired test facility data matched absolute values from a field unit operating at half load. The data from the field unit indicated the NO_x values would increase at most 20% for a factor of two increase in surface area heat release. The information gained from the U-fired Test Facility is being used to design Proof-of-Concept Facility.

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REFERENCES

1. Beittel, R.; Darguzas, J. N.; Ruth, L. A. LEBS Plant Leaves the Drawing Board, Power Engineering, April 1998.
2. Breault, R. W.; Litka, A. F.; Beittel, R.; Darguzas, J. N. SO_2 Control in Low Emission Boiler Systems, the COBRA Process, The 15th SO_2 Control Symposium, Miami, FL March 1995.
3. Schuster, H. "Advanced Coal Firing Systems for Low Emission Steam Generators" Presented at the 11th Annual Pittsburgh Coal Conference, Pittsburgh PA, September 1994.
4. Penterson, C. "Dual Air Zone Burners Surpass Phase II CAAA NO_x Emission Standards for Coal Fired Utility Boilers. Int'l Joint Power Generation Conference and Exposition and the Int'l Conference on Power Engineering, San Francisco CA, July 1999.